Large Scale Distribution of Arrival Directions of Cosmic Rays Above ~100 PeV

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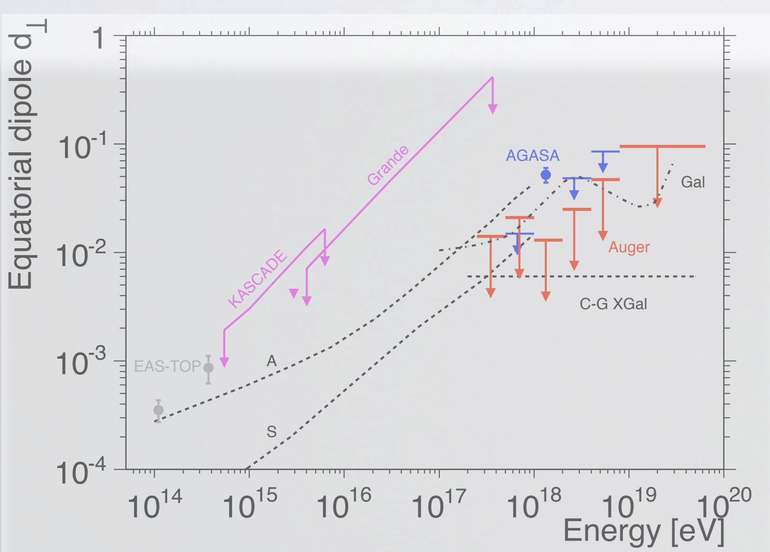
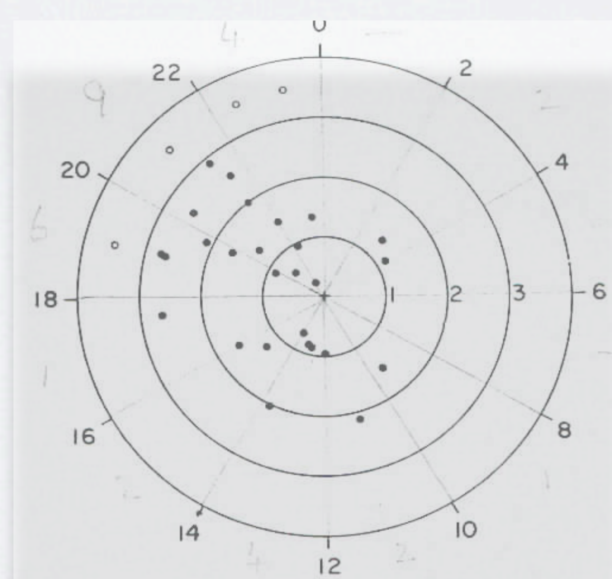
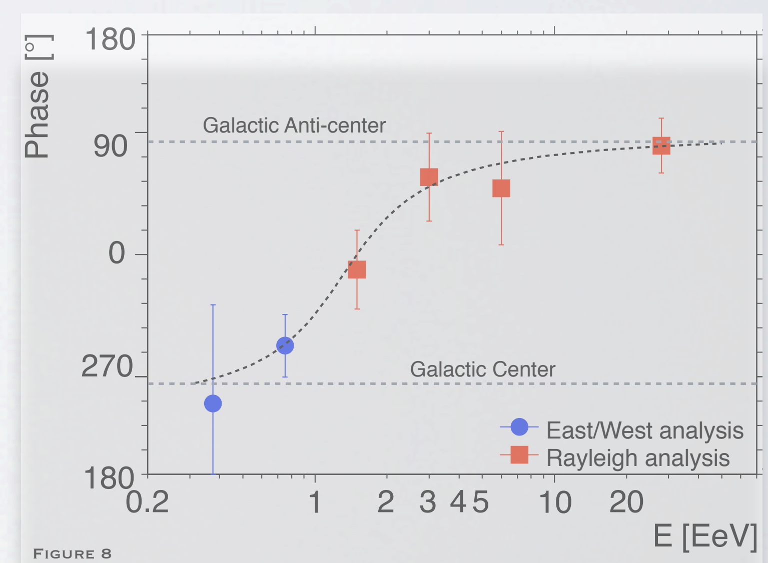
(on behalf the Auger collaboration)

Main reference: Astropart. Phys. 34 (2011) 628

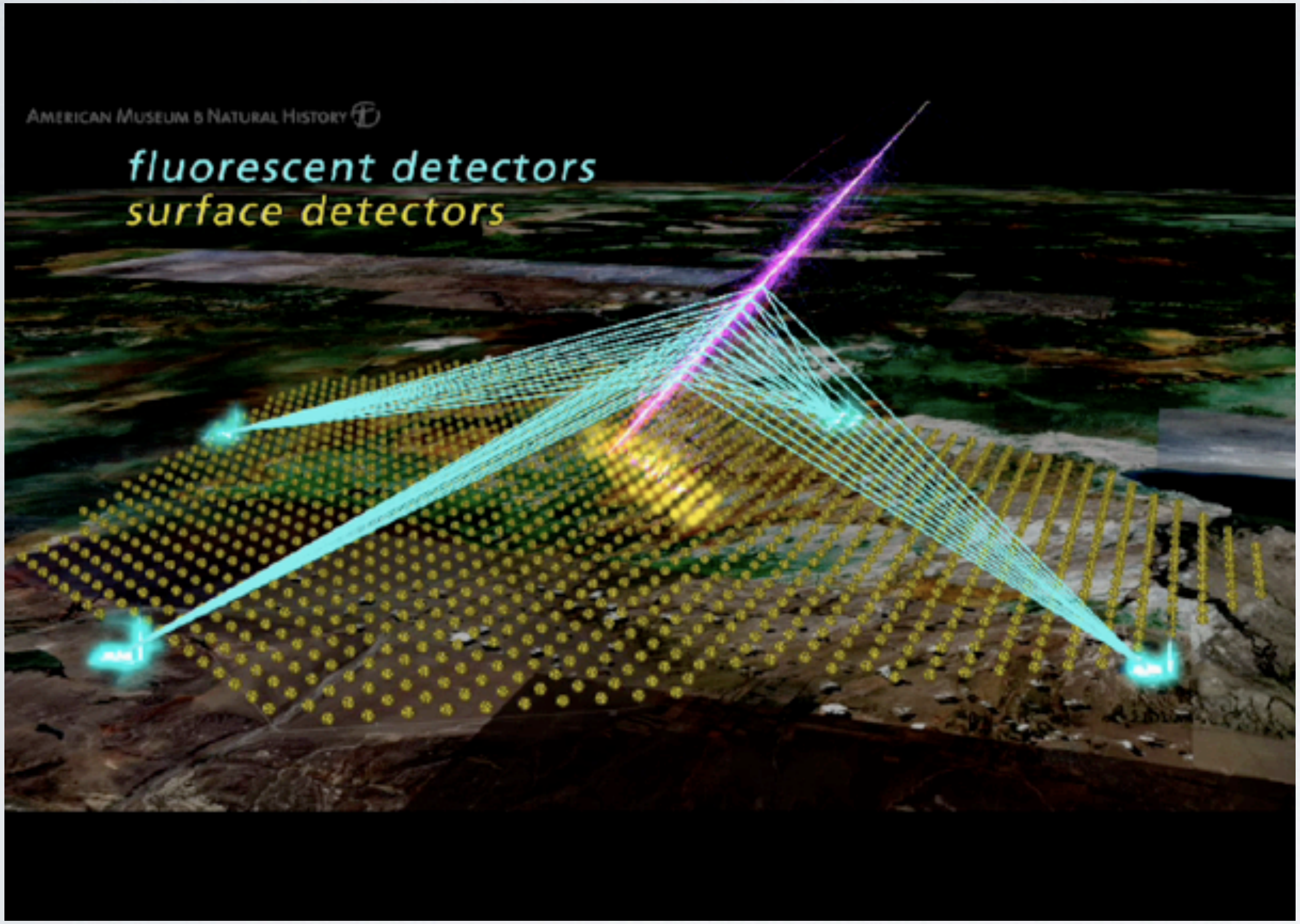






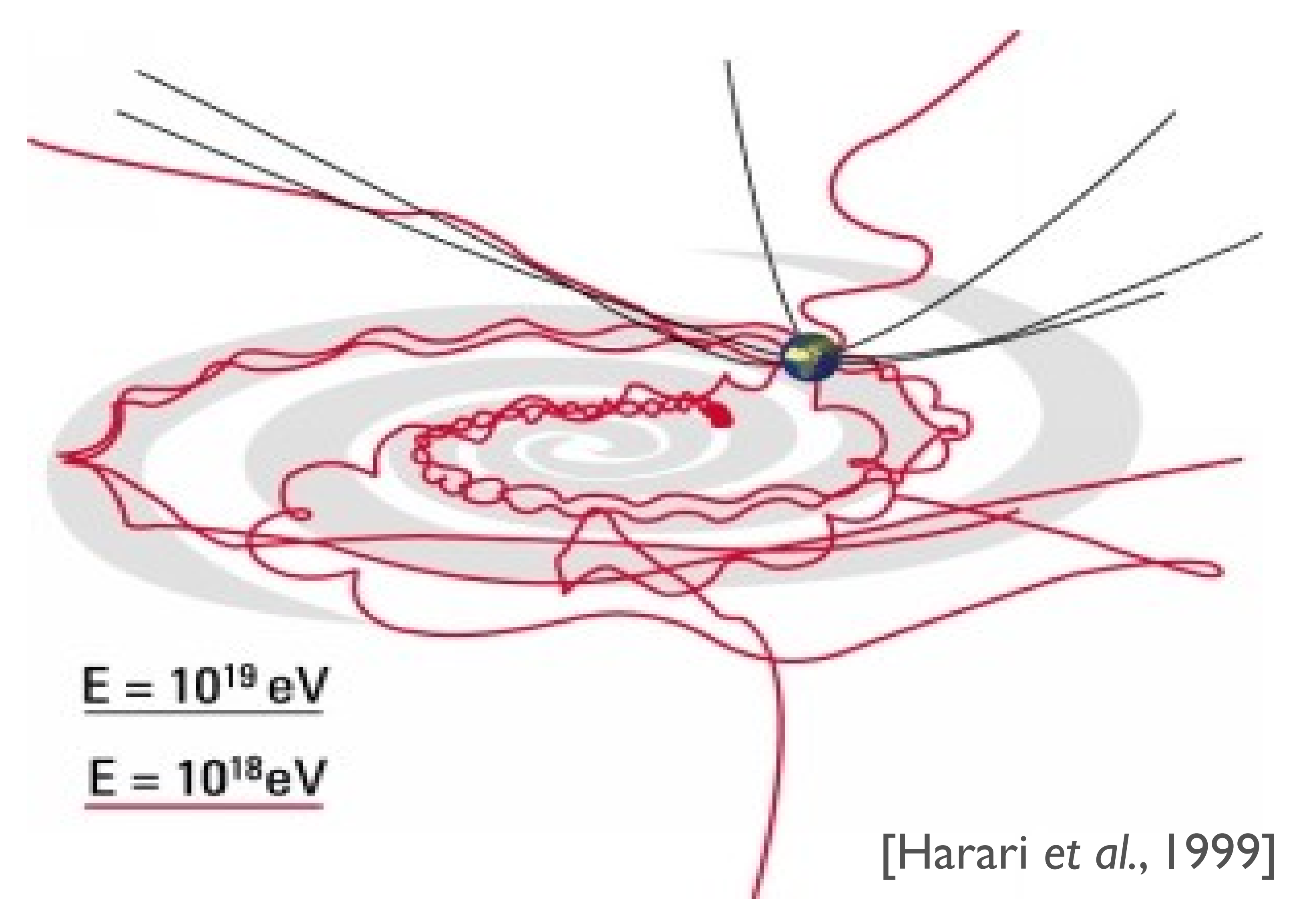
Cosmic Ray Anisotropy Workshop 2011, Madison

The Auger Observatory



- Threshold for full efficiency: 3 EeV
- Median energy: ~300 PeV
- Data set: 01/01/2004 - 31/12/2010
- Exposure: 20,905 km^2.sr.yr

Large scale anisotropies at EeV energies ?



[Harari *et al.*, 1999]

- Time honored picture: the galactic magnetic field can «isotropize» EeV(/Z) CRs: Dipolar anisotropies at the % level could be left by diffusion/ drift motions of galactic CRs
- If extra-galactic, a small anisotropy may exist due to our motion with respect to the frame of extra-galactic isotropy

First harmonic analyses in RA

>1 EeV: Rayleigh analysis

[Linsley, PRL, 1975, 34]

- Dipolar modulations of experimental origin: exposure modulation and «weather effects»

- Compute the Fourier coefficients:

$$a = \frac{2}{\mathcal{N}} \sum_{i=1}^{N} \frac{\cos(\alpha_i)}{\Delta N_{\mathrm{cell}}(\alpha_i^0)}, \quad b = \frac{2}{\mathcal{N}} \sum_{i=1}^{N} \frac{\sin(\alpha_i)}{\Delta N_{\mathrm{cell}}(\alpha_i^0)}$$

$$\rightarrow \quad \begin{aligned} r &= \sqrt{a^2 + b^2} \\ \varphi &= \arctan(b/a) \end{aligned}$$

- Conversion of the shower size into energy taking into account the actual atmosphere to a reference one (OK ≈saturation energy)

<1 EeV: E/W method

[Bonino *et al.*, ApJ, 2011, 738, 67]

- Difference between the counting rate from E/W related to the RA modulation:

$$I_E(\alpha^0) - I_W(\alpha^0) = -\frac{N}{2\pi} \frac{2\langle\sin(\theta)\rangle}{\pi\langle\cos(\delta)\rangle} r \sin(\alpha^0 - \varphi)$$

- Compute the Fourier coefficients:

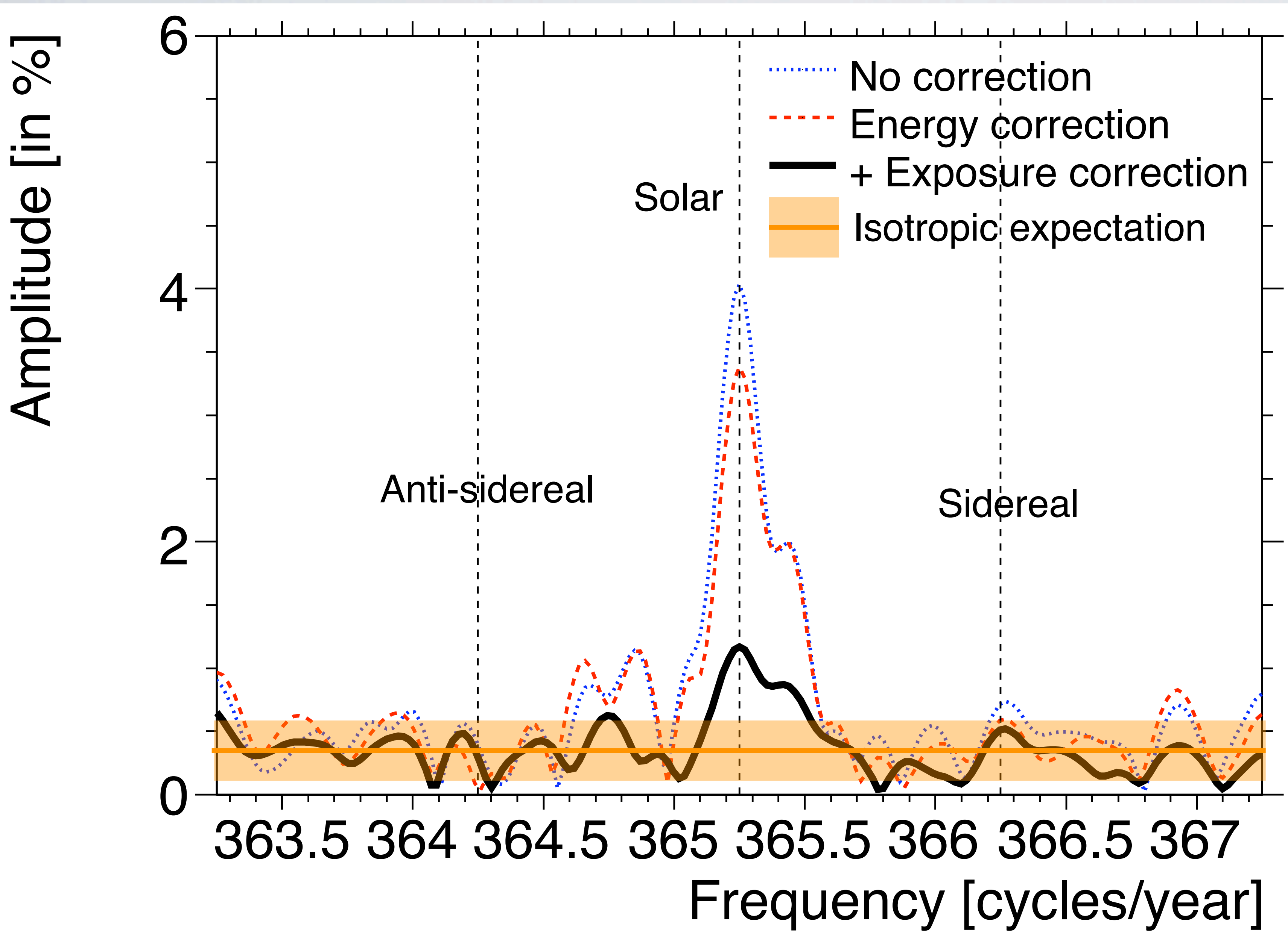
$$a_{EW} = \frac{2}{N} \sum_{i=1}^{N} \cos(\alpha_i^0 + \zeta_i),$$

$$b_{EW} = \frac{2}{N} \sum_{i=1}^{N} \sin(\alpha_i^0 + \zeta_i)$$

- RA amplitude and phase of the dipolar modulation:

$$\begin{aligned} r &= \frac{\pi\langle\cos(\delta)\rangle}{2\langle\sin(\theta)\rangle} \sqrt{a_{EW}^2 + b_{EW}^2} \\ \varphi_{EW} &= \arctan(b_{EW}/a_{EW}) \end{aligned}$$

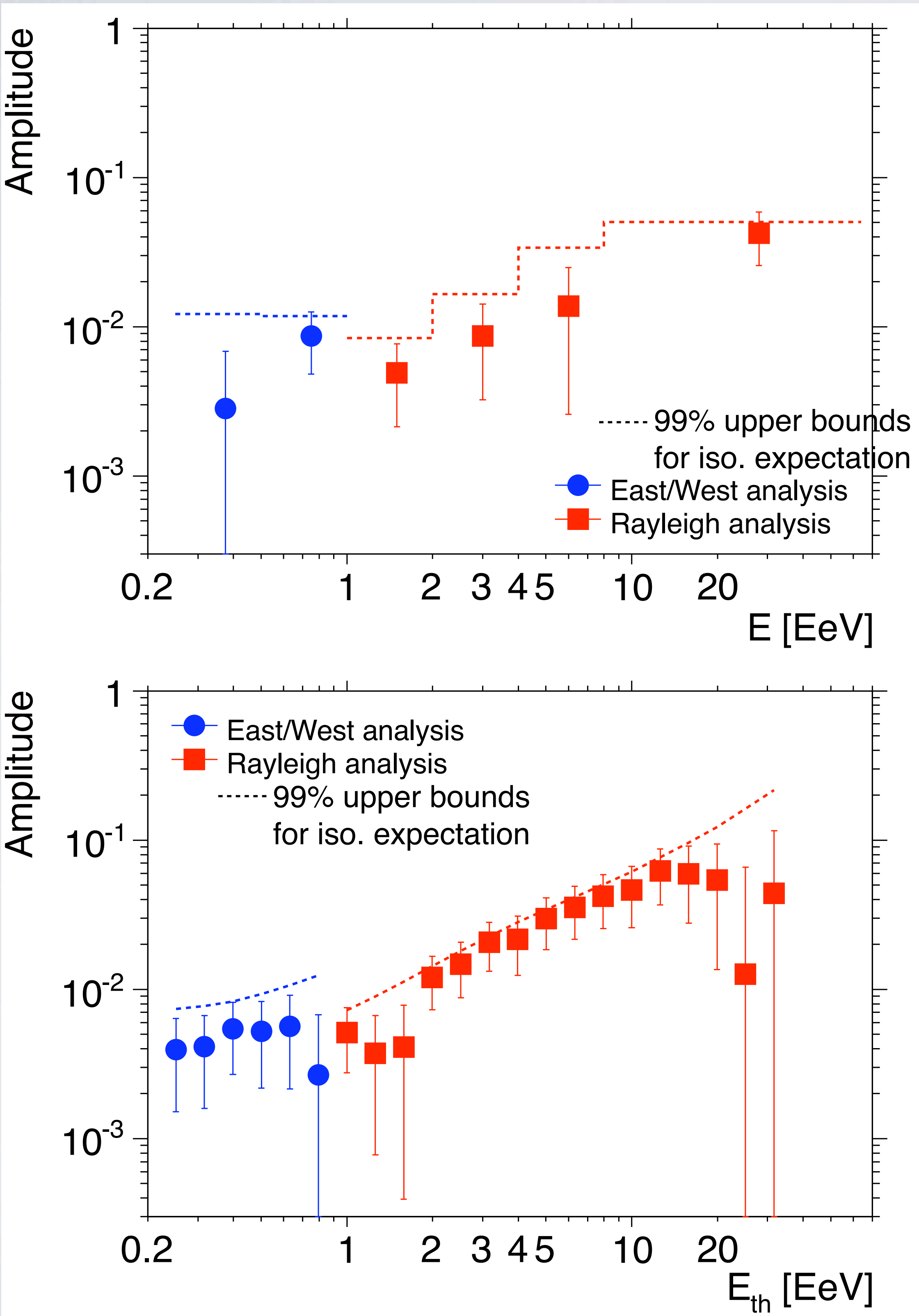
Spectral analysis above 1 EeV



- Decoupling between frequencies clearly observed after 7 yrs
- Amplitudes of random frequencies within noise
- Spurious sideband effect proportional to the solar amplitude: important to correct this frequency

Good control of the exposure and the weather effects above 1 EeV

Analysis of the sidereal frequency



Differential:

- Size of energy bins: $\Delta \log_{10}(E) = 0.3$

  ★ E<8 EeV: below energy resolution

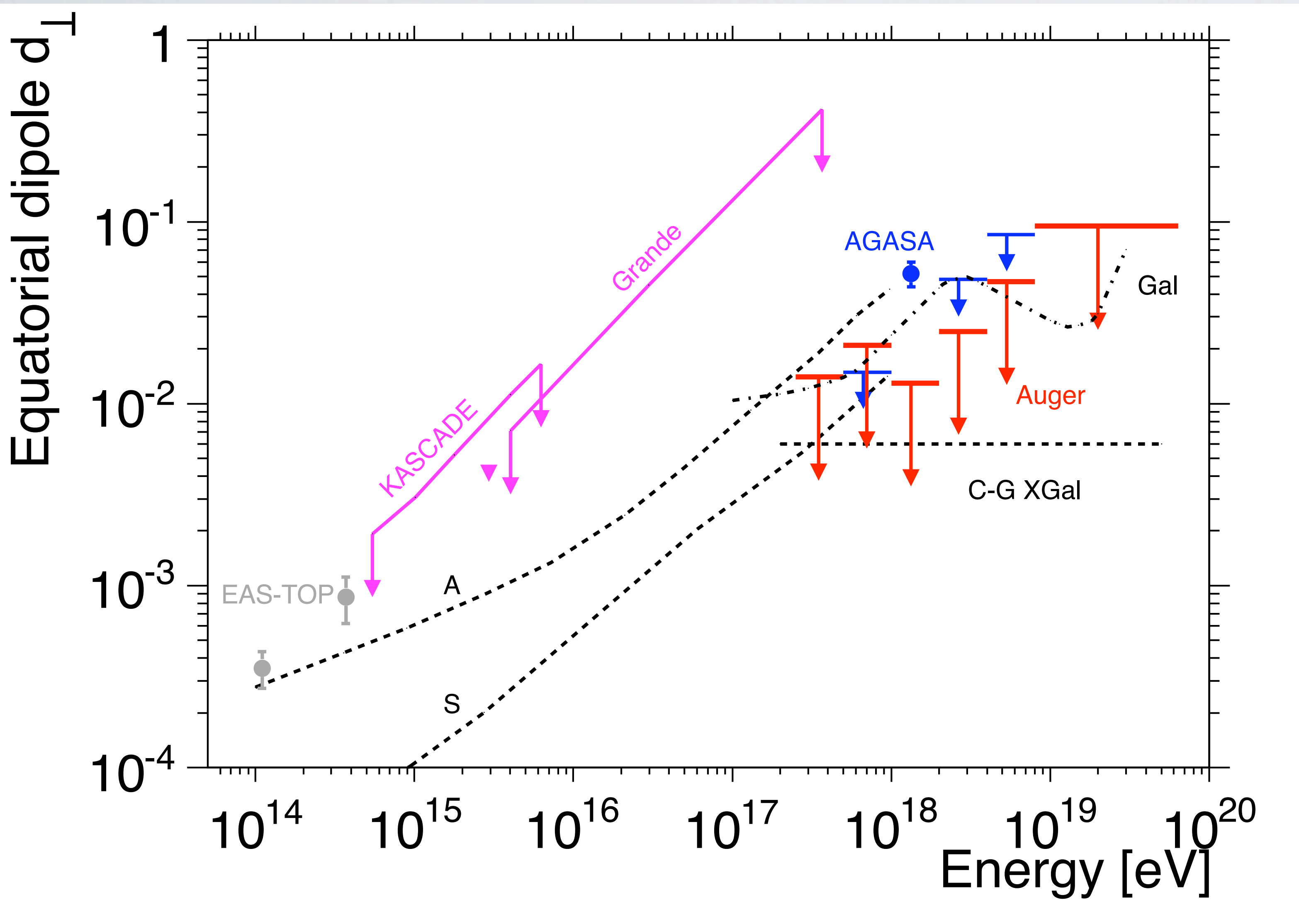
  ★ E>8 EeV: single bin (statistics)

- Combined probability to come from isotropic distribution: ≈45%

Cumulative:

- No further evidence

Upper limits on amplitudes



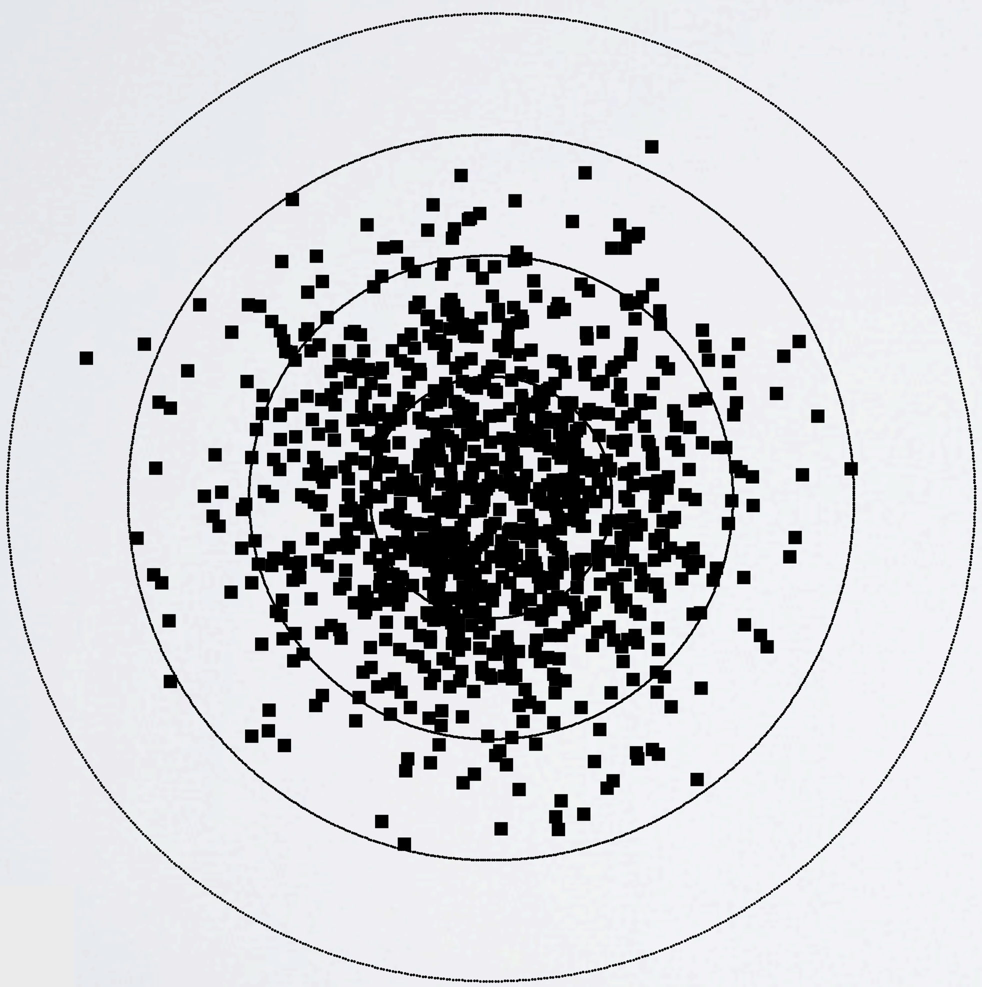
- Raw measurements depend on the latitude of the experiments and on the zenithal range available:

$$d_\perp \simeq r/\langle \cos\delta \rangle$$

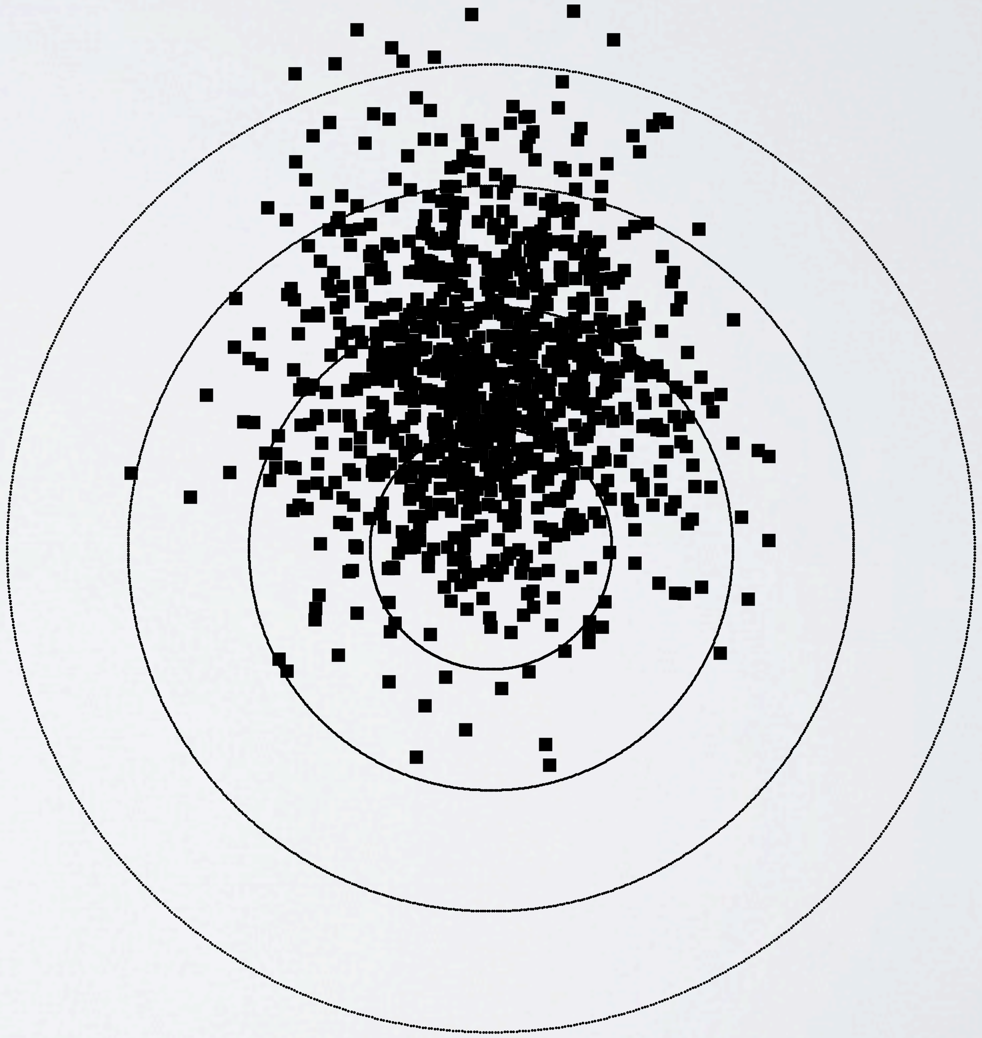
- *Gal*: diffusion in an extended turbulent magnetic field
- *A/S*: drift in the regular magnetic field
- *C-G Xgal*: motion of the galaxy w.r.t the CMB reference frame

Sensitivity to large scale anisotropy: Phases vs Amplitudes

Pure isotropy



Almost isotropy
(signal size = mean noise)



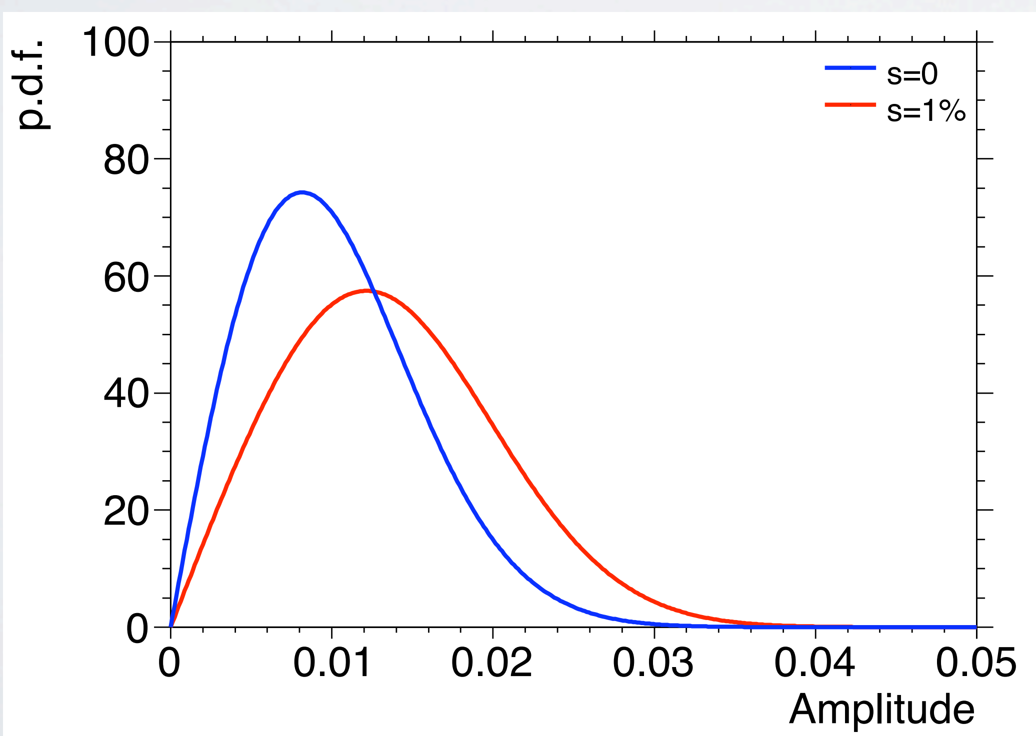
Phase test: Linsley's «2nd alternative»

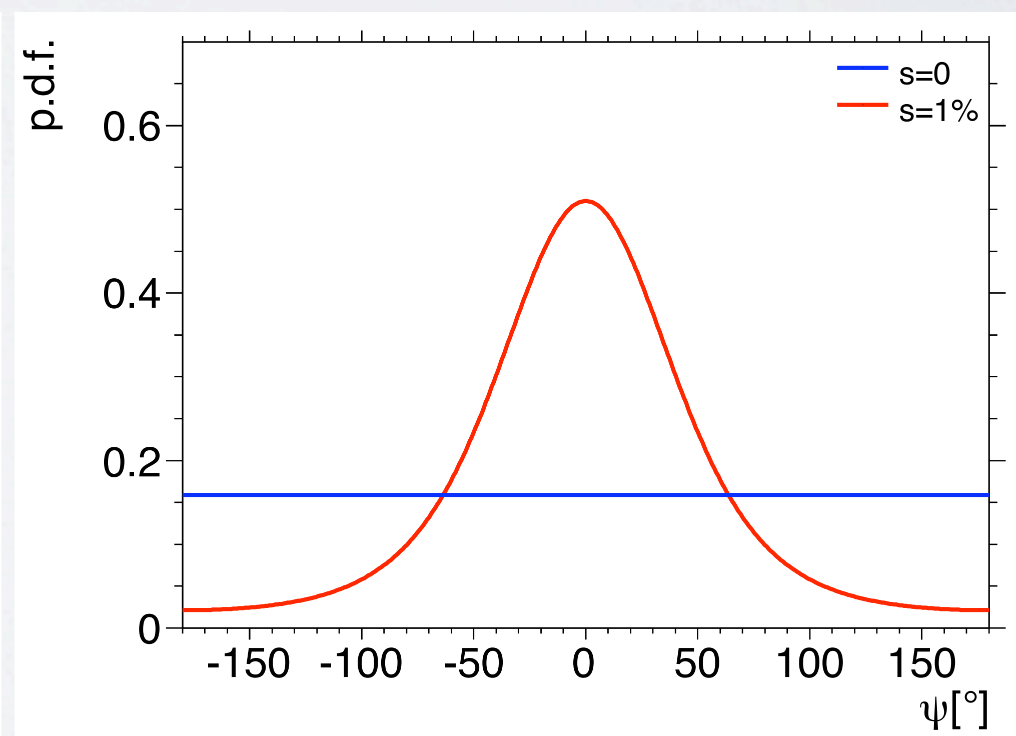
28]. This behaviour was pointed out by Linsley, quoted in [26] : "if the number of events available in an experiment is such that the RMS value of r is equal to the true amplitude, then in a sequence of experiments r will be significant (say $P(> r) < 1\%$) in one experiment out of ten whereas the phase will be within 50° of the true phase in two experiments out of three." We have checked this result using Monte Carlo simulations.

[26] D. Edge *et al.*, J. Phys. G (1978) 133

$$p_R(r) = \frac{r}{\sigma^2} \exp\left(-\frac{r^2+s^2}{2\sigma^2}\right) I_0\left(\frac{rs}{\sigma^2}\right),$$

$$p_\Phi(\phi) = \frac{1}{2\pi} \exp\left(-\frac{s^2}{2\sigma^2}\right) + \frac{s\cos(\phi-\phi_0)}{2\sqrt{2\pi}\sigma}\left(1+\mathrm{erf}\left(\frac{s\cos(\phi-\phi_0)}{\sqrt{2}\sigma}\right)\right)\exp\left(-\frac{s^2\sin^2(\phi-\phi_0)}{2\sigma^2}\right)$$

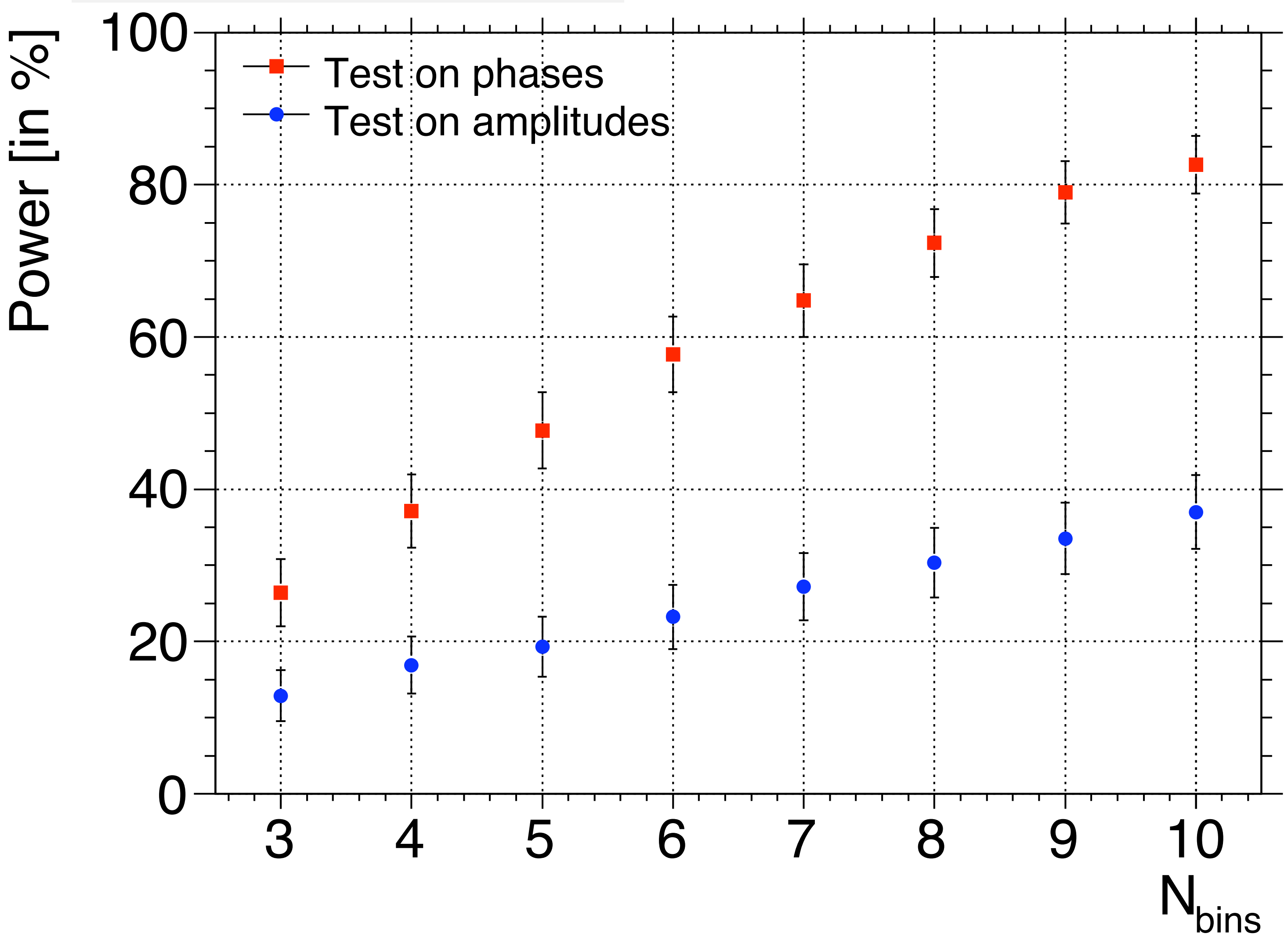




Detection power: phase vs amplitude

Test on the phase for N_b bins

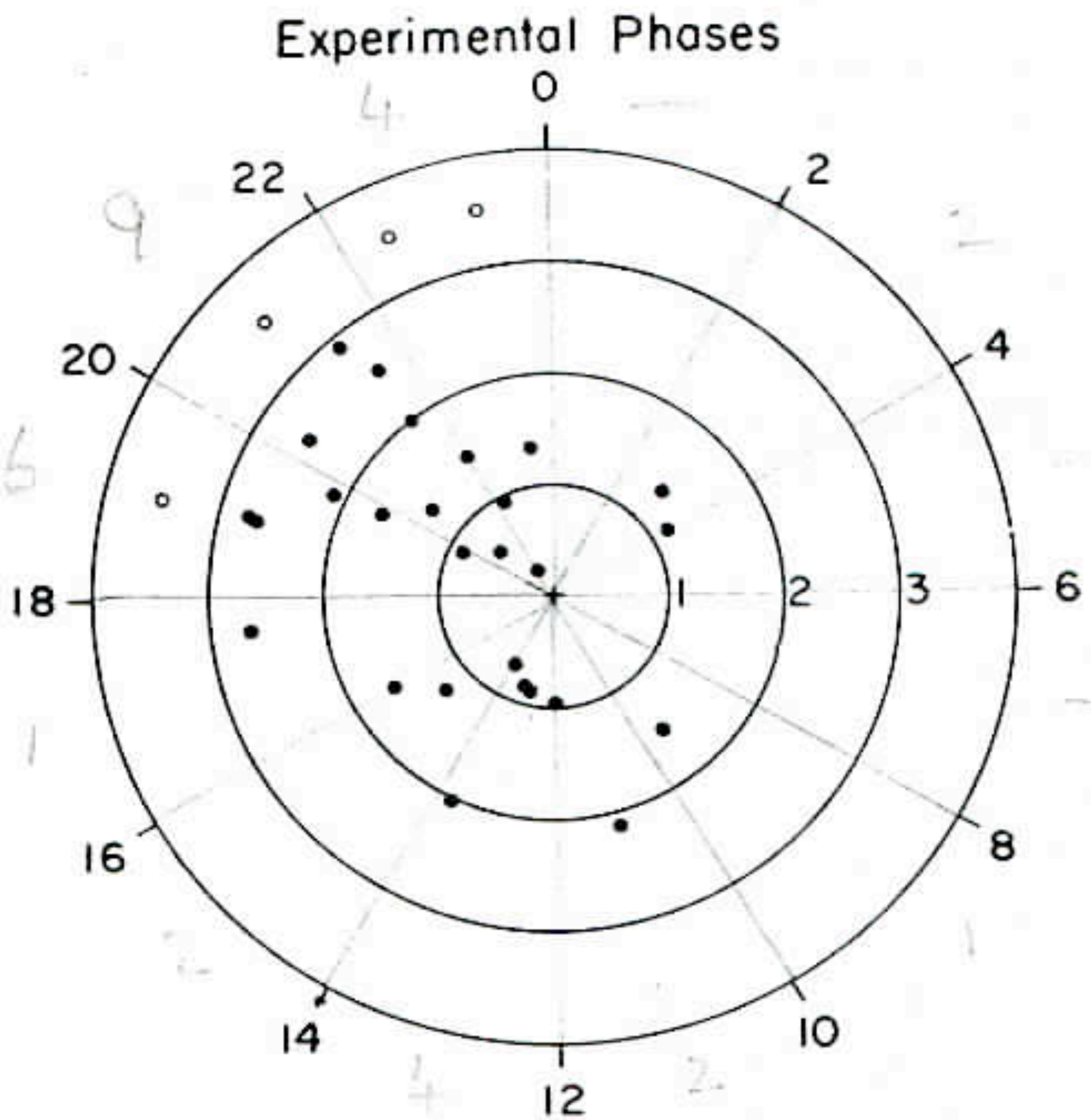
- LL ratio method: $L_0 = \prod_{i=1}^{i=N_b} p_{\text{iso}}(\phi_i)$, $L_1 = \prod_{i=1}^{i=N_b} p_{\Phi}(\phi_i) \rightarrow \lambda = \frac{L_0}{L_1}$
- $-2\ln(\lambda)$ pdf have to be computed
- $p = \int_{-2\ln(\lambda)_{MC}}^{\infty} \text{pdf}(-2\ln\lambda)$



- Phase test ≈2.5 times more efficient
- A consistency of the phase measurement in adjacent energy intervals is thus expected with *lower statistics* than that required for the amplitude to significantly stand out from the background noise

Previous reports on phases

J. Delvaille, F. Kendziorski, K. Greisen, Proceedings of the Int. Conf. on Cosmic Rays and Earth Storms, J. Phys. Soc. Japan (1962) 17 Suppl. A-III 76

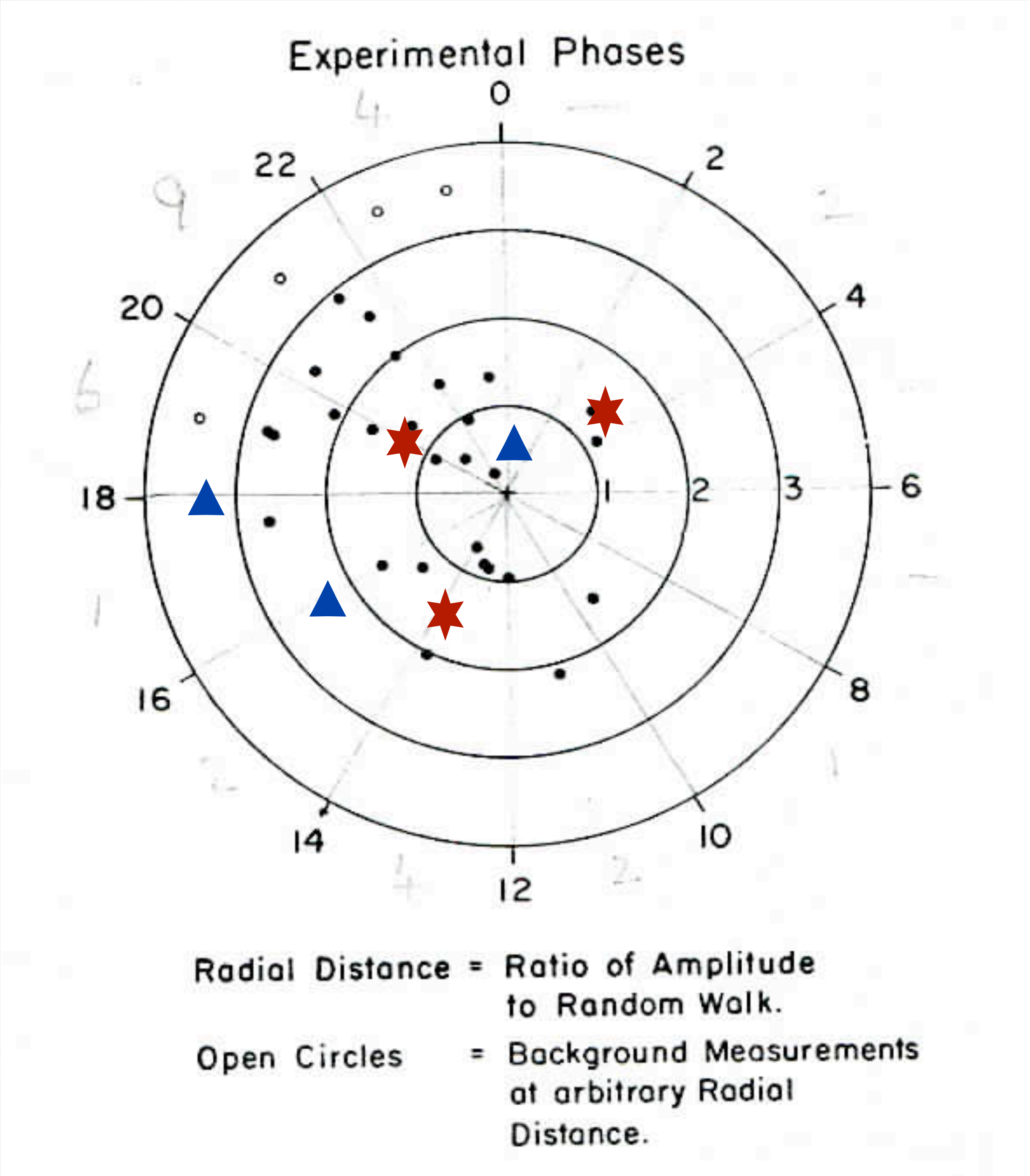


$10^{14} < E/eV < 10^{17}$

One must still account for a remarkable consistency in phase among measurements of primary asymmetry by many different experimenters at different places on the earth.

Since the majority of the EAS experiments have been conducted in the northern hemisphere, atmospheric effects such as those discussed above might account for some consistency in phase of spurious sidereal variations found by different observers. Therefore we regard the reality of these sidereal waves as not yet established, but in need of further investigation, especially by experiments widely distributed in latitude, or at the equator.

Previous reports on phases



$10^{17} < E/eV < 10^{18}$

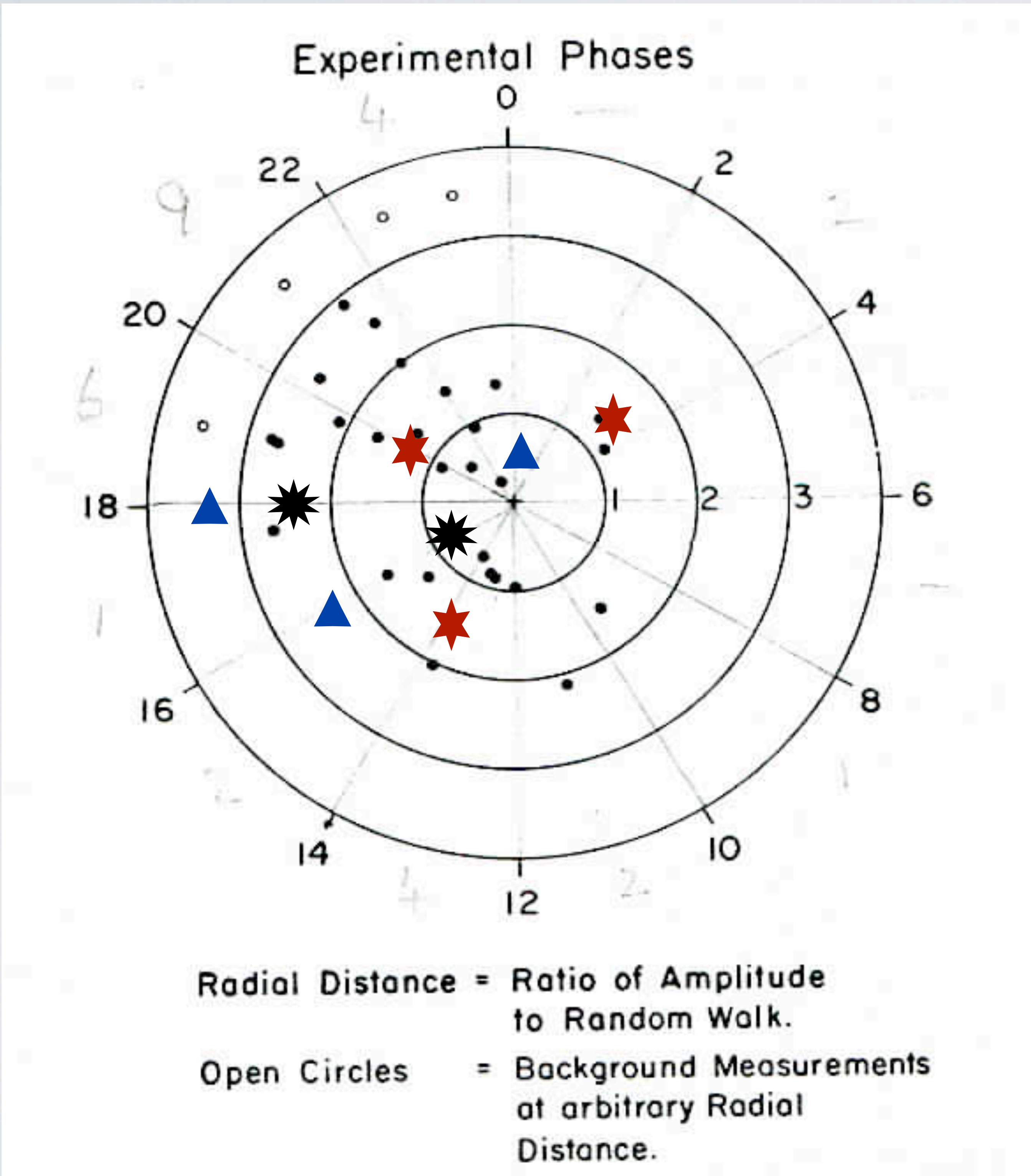
▲ Haverah Park

(From Edge *et al*, Journal of Phys. G, 133 (1978))

★ AGASA

(From the AGASA Collaboration, Astropart. Phys. 10 (1999) 303-311)

Previous/Present reports on phases



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(From Edge *et al*,
Journal of Phys. G, 133 (1978))

AGASA

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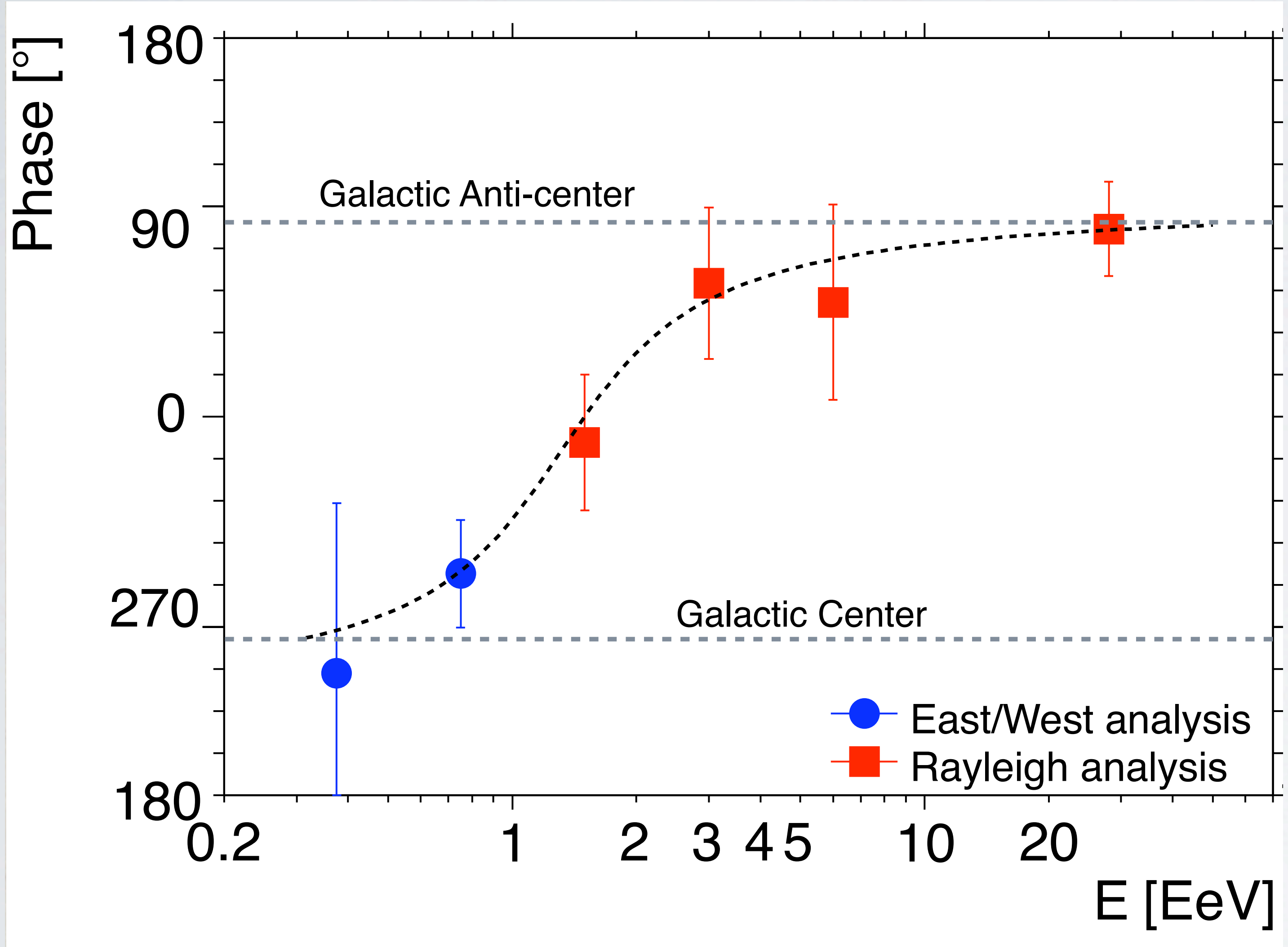
Auger

Future work will profit from the lower energy threshold thanks to the low energy extension of the observatory

Auger results on phases



- Phase measurements <ins>*not*</ins> randomly distributed over the whole energy range: smooth transition from ~270° to ~90°
- *Posterior* probability from the LR test: ~ 0,1%
- Need an independent data set to confirm whether the effect is genuine or not

Future work will profit from the lower energy threshold thanks to the low energy extension of the observatory

Detection of non-zero amplitudes ?

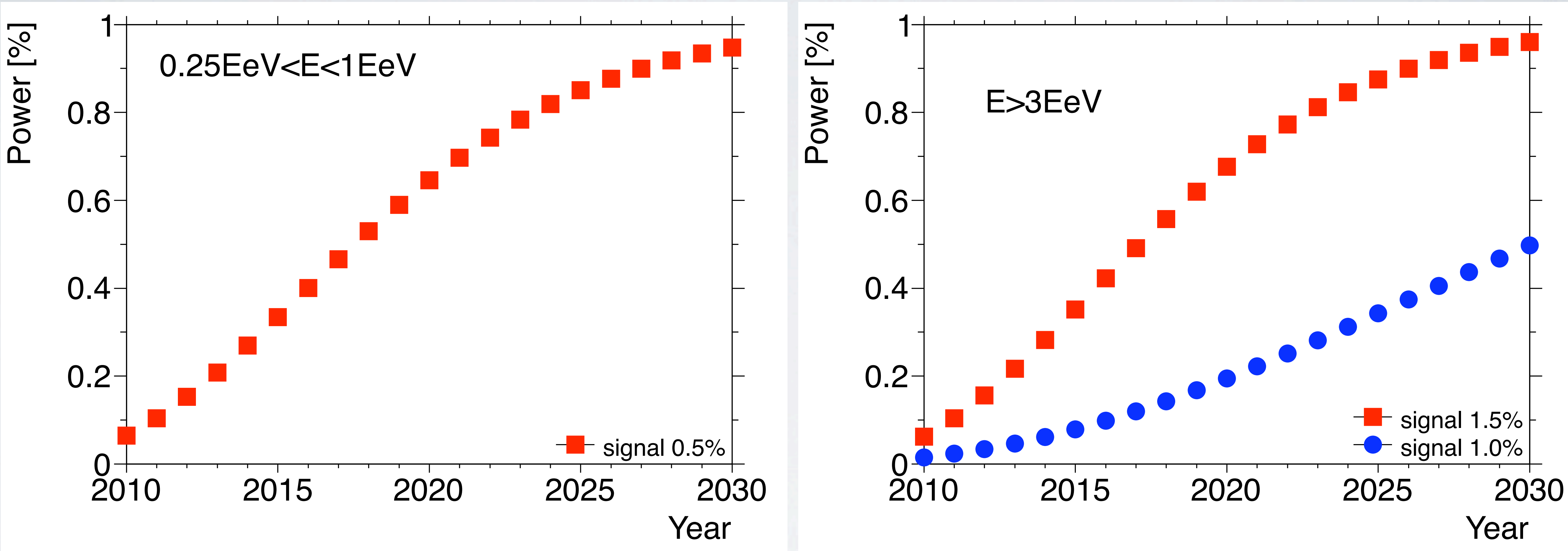
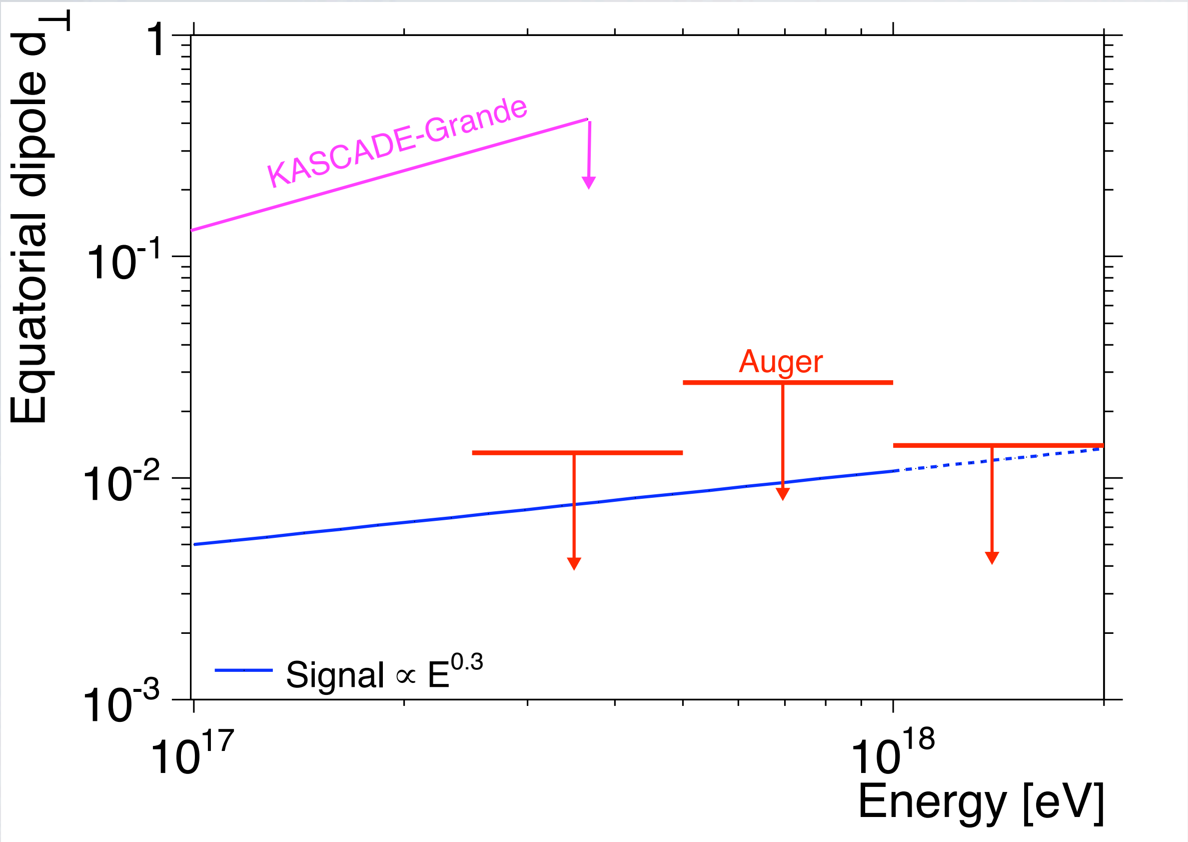


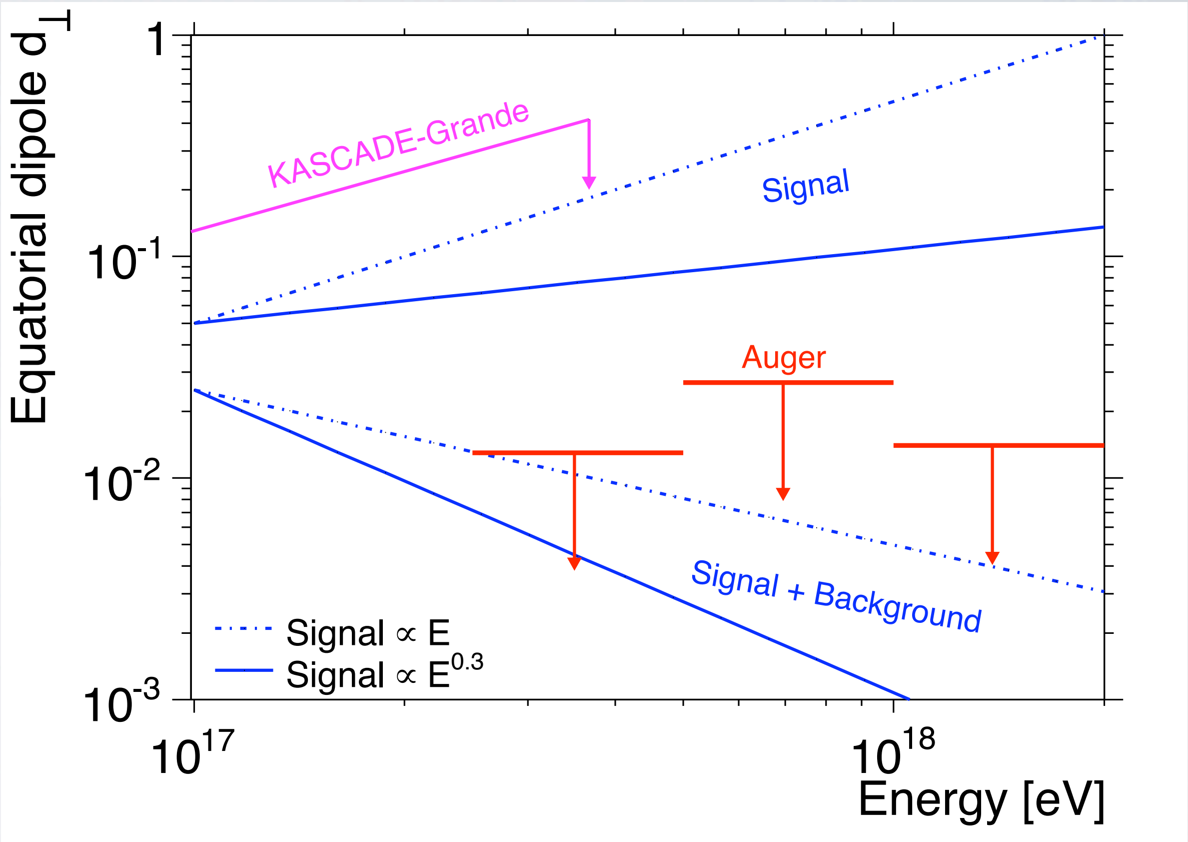
Figure 1: Detection power to measure a dipole amplitude standing out from the background with a significance lower than 0.001 as a function of years. Left : in a single energy bin $0.25 < E/\mathrm{EeV} < 1$, for a signal strength of half a percent. Right : above a single energy threshold $E > 3$ EeV, for two signal strengths.

2 possible scenarios from Auger data

(assuming the phase effect is genuine)



- Main component (proton/helium) slightly anisotropic ?



- Evanescent sub-dominant component highly anisotropic (iron) «snowed» by an isotropic background (proton/helium) ?

Need of anisotropy studies by separating components (masses)

Summary

- No significant measurements of a non-zero first harmonic amplitude
- At EeV energies, stringent bounds obtained
- Consistent phase measurements between ~1 PeV and 1 EeV, close to the RA of the Galactic Center
- Auger phase measurements *not* randomly distributed over the whole energy range: smooth transition from ~270° to ~90° in RA
- Need an independent data set to confirm whether the effect is genuine or not